QUANTUM MECHANICS
in exhibition

Quantum mechanics is the physics of today and in common with contemporary art it is characterised by an unceasing journey, by continuous research. It breaks established rules, tells of what cannot be seen or spoken of, allows for opposites to exist together simultaneously, and makes the impossible possible.

Here we present to you objects and videos that have been made with the aim of providing an insight into certain quantum phenomena, those which we do not experience directly but which underpin our modern technology and lives.

We would love to continue this dialogue once you have finished your journey into the unspeakable. Write to us at iqw2022@ino.cnr.it or on Instagram @italianquantumweeks_ to leave us a comment or to arrange a visit to our research laboratories.

INTRODUCTION

Quantum Mechanics

Our intuition for the laws of physics works well in the macroscopic world. We are not surprised by our ability to handle everyday objects like knives and forks, balls, doors and, with a little bit of practice, cars and aeroplanes. Once we descend to the microscope scale, however, this intuition fails. The laws of classical physics discovered at the beginning of the twentieth century no longer govern.

What is quantum mechanics?

It is complex and unintuitive theory, born to explain the structure of microscopic matter, such as atoms and molecules. Fortunately, this theory doesn't contradict classical physics, but instead makes these old ideas a special case of a more general theory.

Just as the revolution of Newton and Galileo allowed us to calculate how to build bridges and planes, today quantum mechanics allows us to design new materials with innovative properties. It is thanks to quantum mechanics that we can make all the miniaturised devices that make our mobile phones function. And the same goes for dyes, plastics, metal alloys, medicine and biology. Quantum mechanics, born to explain the microscope world, is today found to be fundamental to our understanding everywhere, even on a cosmic scale.

And now we must journey to where quantum mechanics manifests its peculiarities. Let us shrink ourselves down to the size of an atom!

DEPARTURE: METRE SCALE (m)

Top: Nature lovers can imagine themselves in a forest, with trees standing dozens of metres high above our heads like giants.

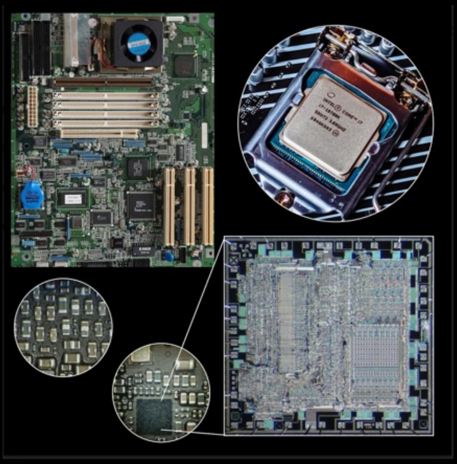
Bottom: Technology lovers can instead imagine being inside a large data farm, where corridor upon corridor wind through thousands upon thousands of computers.

CENTIMETRE (cm) AND MILLIMETRE (mm)

Top: In unspoilt nature we can find spenlid butterflies, such as the Cyanophrys remus, which can sport a wingspan of up to 14 cm.

Bottom: In the data centre, each cabinet contains hundreds of motherboards, like in our PCs, with each made up of many smaller electronic components: processors; resistors; capacitors; chips; and many more.

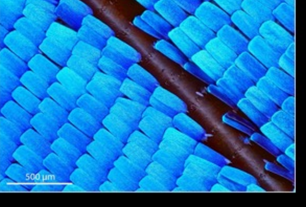
Already with a small magnification we can appreciate new details. In our butterfly, we see that its eye is made up of many smaller structures and the electronic chips are a whole mass of them. To understand better, we must continue our journey to the microscopic.

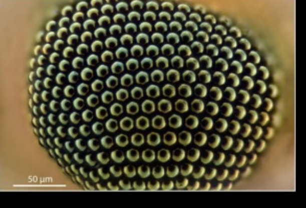


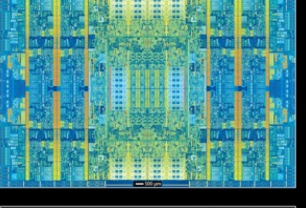
HUNDREDS OF MICRONS:
ONE TENTH OF A MILLIMETRE

Top: nature begins to show its complexity. The eye of the butterfly is composed of thousands of small units, called 'ommatidia', while the wings are covered with special 'scales' whose internal structure gives them their characteristic blue colour.

Bottom: Just as fascinating is a computer processor. It consists of a very thin layer of semiconductor material on which the electrical circuit is made. Here you can see the inside of two Intel processors, a 2020 Core i3-10100 Comet-Lake (colour image) and a Celeron D320 from 2004.



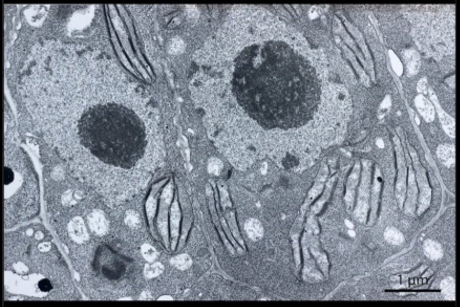


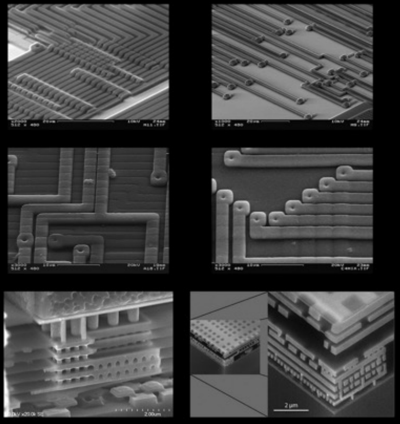


MICRON SCALE: ONE THOUSANDTH OF A MILLIMETRE

Top: electron microscopes reveal to us the cell, the constituent unit of life. Even smaller structures inside it contain the key to its function, such as the nucleus (dark circular region) within which DNA is hidden.

Bottom: we see images of the very thin wires used to distribute small electrical signals inside chips. In the lower part, we see two sections of an AMD Athlon™ 64 processor from 2003, which reveals an even more complex structure.

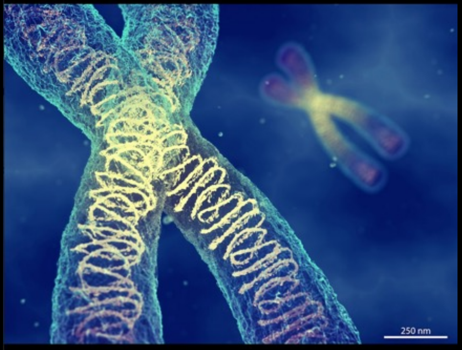


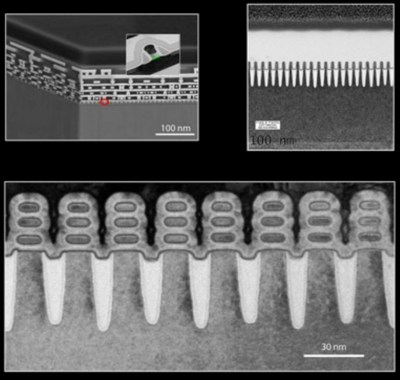


TENS OF NANOMETRES: ONE HUNDREDTH OF A MICRON

Top: : In the cell nucleus we find long chains of DNA. These chains compact to form a chromosome. We can see a reconstruction of a single chromosome, based on a real image, with the yellow strands of AboveDNA within.

Bottom: the nucleus of a processor instead consists of transistors. Analogous to tiny current switches, they are the neurons of every electronic brain. The first image shows a transistor (red) and its gate (green) only 1.3 nm in size. The other images show IBM's nFets, separated by just 30 nm.

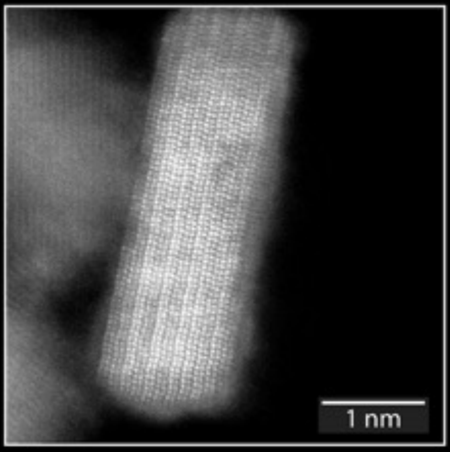




NANOMETRE SCALE: ONE THOUSANDTH OF A MICRON

No, we haven't made a mistake by only putting one image! At the nanometre and sub-nanometre scale, the two worlds, the biological and the technological, are identical. There are only atoms and molecules here. In the picture, you can see individual atoms on the surface of a nanoparticle.

We have reached the destination of our journey to the level where quantum mechanics becomes dominant.



SMART IS QUANTUM

Quantum mechanics in our daily lives

All the semiconductor devices in our smartphones – transistors, CCD cameras, LEDs and Flash memory – are fabricated from components selected for their specific electrical and optical properties. The electrical, optical and magnetic properties of materials are explained by the quantum theory of matter.

In individual atoms, electrons are bound to the nucleus: they are born to move in a region around it and have specific, discrete binding energy values, also called energy levels.

In solids, the presence of many atoms in close proximity to each other modifies the energy levels of the electrons furthest from the nucleus, which are known as valence electrons. This results in the formation of so-called energy bands: intervals of permissible energies separated by forbidden regions or gaps. The properties of materials are determined by how the electrons are distributed in these energy bands.

LET US SEE SOME EXAMPLES

A **CCD** (Charge-coupled device) camera is formed from millions of pixels which are sensitive to the incident light. A single photon, which carries a single quantum of light energy, is absorbed by a single electron. In the process, the electron receives enough energy to jump from the valence band up to the conduction band. It is the electrons in the conduction band that generate the electrical signal which ultimately generates in the image that appears on our screens.

In an **LED** (light-emitting diode) the kinetic energy of the electrons moving within the semiconductor is converted into light energy. The electron falls from the conduction band down to the valence band and emits a single photon equal to the energy gap between the bands. This energy determines the colour of the light emitted and is dependent upon the semiconductor material.

Flash memory is an extremely fast memory device. It consists of billions of special transistors, called floating-gate MOSFETs, which are each capable of storing one bit of memory (0 or 1 in binary). The transistor works like a switch, allowing (1) or not (0) the passage of electrical current. Flash devices retain information even when not powered, thanks to the floating gate devices at its heart. These gates exploit quantum tunnelling, which is a purely quantum effect with no classical equivalent, to trap or release electrical current on demand.

LIGHT & SPECTRA

Let there be light! And there was... quantum light

LIGHT

Light is an electromagnetic wave, characterised by its frequency (the number of periods per second) and its wavelength (the distance between two consecutive maxima or minima). In the visible spectrum, each wavelength corresponds to a colour and has the size of protozoa.

SPECTROSCOPY

No one is surprised to see a rainbow, which is produced when the Sun's rays pass through small droplets of water. This separates the light emitted by the Sun into its component colours, which together make up what is called the **spectrum of sunlight**.

However, we still need quantum mechanics to be able to interpret a simple measurement of the frequency spectrum emitted by different sources.

Look at the different light sources in the room through our **spectrometer**. You will see how the spectra of all these sources are different. This is because all these sources are made from different combinations of elements in the periodic table.

Spectrometer

Take the spectrometer in your hand and point the elongated opening at a light source. Look through the circular hole. You will see the emission spectrum of the source. For the LEDs and gas lamps, there are only scattered lines, which are specific to the material used to make the source. For the light bulbs, however, you will see a continuous spectrum, similar to a rainbow.

Did you know that you can build your own spectrometer? Check out the link in the QR code.

Every chemical element has its own absolutely unique emission spectrum.

Indeed, each element can only emit certain, specific colours. But why? Quantum mechanics gives us the answer!

The energy levels of an atom are like steps in a staircase which are climbed by **absorbing** photons and descended by **emitting** photons. The energy of the photon needed is equal to the size of the step and therefore each step has its own corresponding colour.

THE SUCCESS OF QUANTUM MECHANICS

The atomic model

THE CLASSICAL PLANETARY MODEL

At the beginning of the twentieth century, the existence of **protons**, heavy and positively charged, and **electrons**, light and negatively charged, had already been known for around ten years. In analogy to the solar system, it was initially imagined that electrons orbit the nucleus, with the centrifugal force balanced not by gravity but by electrical attraction.

But this model had serious problems. Firstly, an electron following a curved path like an orbit always emits light, but no light is observed glowing from atoms. Secondly and moreover, the energy levels of an atom are not continuous, but takes only certain discrete values.

THE SEMI-CLASSICAL MODEL OF BOHR

In 1913, **Niels Bohr** hypothesised an atomic model in which the energy of the electrons can only be discrete, well-defined values, by arranging the energy levels as different orbits of increasing radius. Furthermore, electrons remain in the same energy level (orbit), unless the atom interacts with light or other particles. But this model still cannot explain certain other experimental observations, such as the fact that these energy values change in the presence of a magnetic field.

We reproduced an oxygen **atom** – try and find it on the periodic table! - using Bohr's semi-classical planetary model. Here the negatively charged electrons are spherical and well localised and move in concentric orbits around the heavy, positively charged nucleus.

THE QUANTUM MODEL

Quantum mechanics through the contributions of **Heisenberg** and **Schroedinger**, resolved all the problems and incongruities through the introduction of a new paradigm. We can no longer simultaneously know the distance of an electron from the nucleus and its speed. Therefore we no longer speak of orbital trajectories.

We have instead the new concept of an **orbital**. This describes the spatial distribution of an electron for a given energy, that is, the probability of finding the electron in a certain position around the nucleus.

With this new theory, how electrons do not fall but instead stay bound to the nucleus is mathematically clear, but entirely without analogue in the classical world we know.

THE DOUBLE-SLIT EXPERIMENT
seeing the quantum superposition

The abandonment of classical theory in favour of a more complete description has astonishing consequences. Let's look at these three amazing experimental examples!

THE DOUBLE-SLIT EXPERIMENT: THREE CASES COMPARED

Sand dropped through a pair of slits will land in two distinct piles. For every grain, we can say with certainty which of the two slits it has passed through and the precise point where it lies afterwards.

When an **electromagnetic wave** (light) passes through a pair of slits it generates an interference pattern, with alternating regions of light and darkness. When wave crest meets a trough, the interference is said to be destructive and the intensity of the light is zero. It is not possible to speak of a precise point where the wave is measured because it is a phenomenon that encompasses an entire region of space.

A **quantum particle** behaves in yet another way. Every single **electron** is observed to land in a single point, like a grain of sand, but it is not possible to reconstruct where it came from. When a large number of the electrons have passed through the slits, they are seen to be arranged into an interference pattern.

In order to explain the behaviour of a quantum particle, therefore, it is at least partially necessary to abandon classical ideas of motion with precise trajectories. Instead we must meld these ideas with some of those more commonly associated with waves.

IN MORE FORMAL WORDS:

When we only have a single silt, there is likewise only one possible state for the electron. A repeated series of measurements on a screen behind the slit reproduces the spatial probability distribution of the electron, or the probability of it being found at any particular point in space. This probability function is the square of the so-called **wave function** which describes the state of the electron.

It is only when we add a second slit that there are two possible paths for the electron and there are two possible wave functions. These wave functions add up to produce an interference pattern with a series of crests (yellow in the picture) and troughs.

BISTABLE CATS AND WHERE TO FIND THEM

Seeing the unspeakable with optical illusions

The existence of **superposition states**, whose constituent components cannot be observed at the same time, is one of the seemingly paradoxical features of quantum theory that calls for the development of a **new logic**, different from the classical case.

Although as the quantum theorist Paul Dirac said “the superposition that occurs in quantum mechanics is of an essentially different nature from any occurring in the classical theory”, we can illustrate it visually by means of **bistable images**. In these optical illusions, two incompatible visual interpretations of the same image coexist in a state of superposition. When we observe the image, only one interpretation is visible at a time.

Necker cube: an image with bistable perception introduced by the crystallographer Louis Albert Necker in 1832.

Rubin's vase: a famous series of bistable images developed around 1915 by the Danish psychologist Edgar Rubin, cousin of Niels Bohr.

THE CRUCIAL ROLE OF OBSERVATION: THE STATE OF SUPERPOSITION COLLAPSES INTO ONE OF THE TWO POSSIBILITIES WHEN OBSERVED

A question we can ask ourselves is what is the configuration of a state that is not observed?

As Einstein put it, “do we really believe that the moon isn't there when nobody looks?”. Or thinking instead of **Schroedinger's famous cat**, can we really not say whether a cat in a box is alive or dead until we open it?

THE RULES OF THE Q-GAME

or the axioms of quantum mechanics

While the success of quantum mechanics in explaining the microscopic world is undeniable, accepting its principles necessitates us to give up many of our ideas about reality.

PREPARATION OF AN INITIAL STATE

The axioms of quantum mechanics decree that the properties of physical systems, such as position, are described by a **state**. The associated wave function (shown as a pyramid or cube) gives information on the probability that the quantum system will be found in a certain position.

STATE EVOLUTION

The wave function **evolves** according to Schroedinger's equation and can also be in a **superposition** of opposite states (pyramid + cube)

MEASUREMENT

The process of **measuring** the physical quantity of interest, for example the position of a particle, results in the **collapse** of the wave function into a given position (ball) that corresponds to the information we have available and observe about a system classically.

POLARISATION AND POLARISERS

Light is composed of **electromagnetic waves** that propagate through space. The plane in which electric field is oscillating defines the polarisation of the wave. We can easily see how this property of light is present in our everyday lives.

Let's take a **polariser**, which is an instrument that alters light based upon its polarisation. These are found, for example, in polarising sunglasses, which eliminate reflections from horizontal surfaces such as the glare from the sea.

We can imagine the polariser as a small grid which only allows light to oscillate in one direction. For microwaves, these grids are so large that we can see them with the naked eye. For visible light, however, the grids are much smaller, but the idea is the same.

Even **photons**, the particles that make up light, are polarised. As they are the quanta of the electromagnetic field and cannot therefore be further sub-divided into smaller parts, when they encounter a polariser they either pass through or are stopped. Part of a photon cannot pass through – it is all or nothing.

Let us see now how we can use the polarisation of classical light to learn about quantum mechanics.

LET'S PLAY WITH POLARISATION!

Measurement, commutation, superposition and mixed states

For this measurement you will need the set of three polarisers in this room. Rotate them and notice how the light passes through them for various different configurations.

STATE PREPARATION

We begin by preparing a quantum state using the first polariser.
Ex.1 Prepare the first state by orientating the first polariser vertically (V)

MEASURING THE STATE

But how do we know that everything is working well?
Polarisation can be measured by using a second polariser. The amount of light transmitted through the second polariser gives us information about the probability that the photons are polarised parallel to the polarisation axis.
Ex. 2 Measure the vertical state previously prepared by rotating the second polariser first to the vertical position and then horizontally. When the two polarisers are orientated in the same direction, the transmitted light is maximised. Similarly, when they are perpendicular, the transmission is at its minimum.
Ex. 3 Repeat the measurement by preparing a diagonal initial state by orientating the first polariser at 45 deg. In this case, the same amount of light is transmitted when the the second polariser is in the vertical and horizontal states because the diagonal state is equivalent to an equal superposition of horizontal and vertical polarisation.

WAVE FUNCTION COLLAPSE

Let us now consider a very special feature of quantum mechanics, the fact that the simple act of **measuring a physical system has an effect on the system itself**. As you have already seen, this property is known as 'wave function collapse'. Once the polarisation of the state has been measured, its polarisation has 'collapsed' and is now equal to that of the polariser. This phenomenon leads to some very interesting results! Let's look at one now

Ex. 4 Prepare the vertical state again. As we have seen, when measuring in the horizontal direction, no light is transmitted. But now here comes the weirdness! We can insert a third polariser in between the first two, orientated diagonally at 45 deg. Now light passes through all three polarisers! This is because once light has passed through the second polariser its polarisation becomes diagonal and then pass through the third, horizontal polariser. This simple experiment shows us how a state can be modified by the act of measurement, just as happens in quantum mechanics.

THE BLOCH SPHERE: BITS AND QUBITS

THE REPRESENTATION OF A QUANTUM STATE

The superposition of two quantum states has a precise mathematical description and a geometric counterpart, the **Bloch sphere**. We begin by thinking about the superposition of two states of polarisation or energy, which we call 0 and 1. To represent these states and their superposition, we use a sphere, like Earth. The state 0 is represented by the North Pole and 1 by the South Pole. A quantum state can be in a superposition between these two places, with a say 30% chance of being at the North Pole and a 70% chance at the South Pole. That is, although we are most likely to find it in Antartica, we may also find it in the Arctic! **The probability of finding the particle in at the North or South Pole is represented by the latitute of the state on the sphere.** At the equator there is an equal chance of finding the particle at one of the poles. But there is an important point – whenever we measure the position of the particle, we can only find it at one of the poles and never in temperate or tropical zones. **All points on** Earth's sphere, or in quantum mechanics **the Bloch sphere, represent possible states of superposition**. Points at the same latitute can differ in longitude, depending on how the two states 0 and 1 sum up, just like in the double-slit experiment the result depends upon whether two crests meet eachother or a crest and a trough. To fully describe the state of the simplest quantum system, however, an entire sphere is needed.

LOGICAL COMPUTATIONAL UNITS

A two-state quantum system, 0 and 1, can be used as a logical computational unit. The classical equivalent, the bit, is a variable that can only take two values 0 or 1 (or true/false, high/low, north/south, etc.). In classical computers of the everyday world, bits are made from transistors. When a transistor flows current it is in state 1, when it interrupts current it is in state 0. Sequences of bits are used to encode numbers, text and programs.

In a quantum computer, bits are replaced by qubits. Since a qubit can be in a state of superposition, **the number of possible configurations is much larger than the classical case and there are many more possible actions that we can perform.**

In the classical case, as long as we limit ourselves to a single bit, the only way we can modify it is to change its value from 0 to 1 or vice versa. In the quantum case, conversely, it is possible to transform any state into any other by means of rotation upon the Bloch sphere.

PLAY WITH THE BLOCH SPHERE

Here the logical space of a qubit can be explored, whose representation is different from the classical one. By moving the magnet on the surface of the sphere logical transformations can be made: by pointing the magnet to the poles, the qubit takes the value 1 or 0. However, by moving it to any other point on the surface, they will fall in the superposition states of 0 and 1.

THE Q-RUPIER ALWAYS WINS

the coin game

THE CLASSICAL GAME

Possible states of the coin head (**T**), tails (**C**)

The players are free to choose between flipping the coin(**F**) or not (**I**)

0) The initial state of the coin is **T**
1) Player 1 plays **F** or **I** without showing the result
2) Player 2 plays **F** or **I** without looking at the coin
3) The coin is observed

Solution:
Player 1 wins if the coin's state is **T**, Player 2 wins if the coin's state is **C**
Statistically, each player wins 50% of the time

THE QUANTUM GAME

Possible states of the quantum coin are **T** (north pole) and **C** (south pole)

Classic Player Rules: flipping the coin corresponds to a rotation of around X of 180 degrees. The player can choose whether to flip (**F**) or not (**I**).
Quantum Player Rules: they can make any rotation, for example from the state **T** to the state **S** (see figure)

0) The initial state is in **T**
1) The player rotates around R creating **S**
2) The classic player can play **F** or **I**.

The result does not change! The quantum player is able to make the flip ineffective by using a move that is not possible classically!

3) The quantum player can transform S into **T** (same rotation around the R axis)
4) The coin is observed

The quantum player, with this trick, always wins!

The quantum player is able to make the flip ineffective by using a move that is classically not possible (same rotation around the R axis)

From this example we can understand how quantum technologies, as well as the quantum computer, can perform better than any classical analogue

THE QUANTUM COMPUTER
is a reality

The realization of the fact that the quantum effects like the superposition and entanglement could provide an advantage to the solution of many problems started with the Feynman's proposals in 1980s.

For example, to represent all states with classic bits assuming 64 qubits alone, almost 150 exabytes of memory are required (millions of gigabytes) which is equivalent to about half of all global information processed between 1986 and 2007.

You would have never imagined that the matter that surrounds us could turn into a quantum computer? To realize a qubit in real life, it should be understood in the following system

1) two-level quantum (one photon, one atom, one electron)
2) manipulated from the outside
3) from which information can be extracted.

HOW IS A QUANTUM COMPUTER MADE?

In a **quantum computer with cold atoms**, a single atom is isolated and trapped in an artificial optical lattice (see illustration - the atoms are the coloured balls) and cooled to temperatures of the order of milli-Kelvin, constituting the quantum system exploited to encode and process the information. The photo shows the quantum simulator that operates with 256 qubits, created by scientists from Harvard University and MIT.

In a **photonic quantum computer**, it is necessary to manipulate and make the individual photons interact. The component keys are the sources of single photons, lens systems, mirrors and detectors sensitive to the single quantum of light. An advantage of such system is it's ability to operate at room temperature. In the photo, the quantum computer (**100 qubit**) can be seen that is produced at the University of Science and technology Hefei (China).

A **superconducting quantum computer** takes advantage of superconducting electrical circuits in which the quantum system consists of pairs of electrons. Cryogenic systems are used for temperatures below -272.15 ° C, necessary for superconductivity, and microwave electronics to control and read the qubits . The photos (left) show the details of the superconducting processor of IBM at **127 qubits.**

Use the QRcode to listen to the first music compilation composed by 16 qubit superconducting quantum computer at IBM Guadalupe!

QUANTUM CRYPTOGRAPHY
the application is already in use

CLASSICAL CRYPTOGRAPHY

We continuously use encryption protocols to:
- withdraw cash
- make online payments
- send whatsapp messages

If Alice and Bob (two users) want to swap information that Eva (the spy) must not know, they can exchange a **key** (a secret phrase) to encrypt their messages. The security in classical cryptography is dependent on the strength of the complexity of the mathematical algorithms used for the generation of codes. Therefore, Eva finds a computational difficulty in finding the encrypted messages. However, If Eva intercepts the key during the exchange between Alice and Bob, she can decrypt all the information that Alice and Bob exchanged.

QUANTUM CRYPTOGRAPHY

Quantum mechanics has solved this issue. Indeed, the secret key exchange protocols based on quantum mechanics allow us to identify the presence of Eva if, she attempts to intercept the key. Thanks to quantum superposition and the quantum measurement process, it has become possible! It changes the status of the measuring system. So if Eva has access to the communication channel and tries to measure the key, Alice and Bob will notice that and they will not use the compromised key.

In figure:

Alice: So, I dropped the key in a series of qubits and sent it to Bob

Eva: Damn! If I intercept the key, Bob will know!

Bob: I measured the qubits and reconstructed the key.

Example of device for quantum key distribution developed by Quantum Telecomunication Italy S.r.l. (Florence).